다중 시간지연 공정을 위한 개선된 다중루프 PI 제어기 설계

Design of Advanced Multi-loop PI Controller for Multi-delay Processes

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Abstract: An analytical method for robust design of the multi-loop proportional-integral (PI) controller is proposed for various types of multi-delay processes. On the basis of the direct synthesis and generalized IMC-PID approach, the analytical tuning rules of the multi-loop PI controller are firstly derived for achieving the desired closed-loop response, and the structured singular value synthesis is then utilized for the tradeoffs between the robust stability and performance by adjusting only one design parameter (i.e., the closed-loop time constant). To verify the superiority of the proposed method, the simulation studies have been conducted on a wide variety of multivariable processes. The multi-loop PI controller designed by the proposed method shows a fast, well-balanced and robust response with the minimum integral absolute error (IAE) in compared with other renowned methods.

Keywords: multi-loop PI controller, robust control, generalized IMC-PID approach, structured singular value

I. INTRODUCTION

The multi-loop proportional-integral (PI) control algorithm has widely accepted in most industrial applications because of its practical advances, such as the simplicity of control structure, the efficiency of implementation, and robust performance. Although many advanced control techniques have been reported for achieving the significant improvement of overall performances, i.e. the model predictive control (MPC), a vast range of multi-loop PI controllers have proved to be a standard utility routine for control system construction. The performance of multi-loop control systems is usually not better than advanced control techniques in advance. However, due to their above advantages, many multi-loop design methods have been introduced in the literature. However, a large number of existing design methods are based on the extension of single-input, single-output (SISO) PI controller design methods due to the complexity of loop interactions [1-4].

To find a simple and effective design method of the multi-loop PI-type controller with the significant performance improvement has become an imperative research issue for process control engineers. According to Truong and Lee [5], a systematical method is suggested for the tuning of multi-loop PI controllers, which can directly bring loop interactions into consideration, the proposed method deals with two major steps: as a first step, the analytical tuning rules of the multi-loop PI controller are derived from the basis of the direct synthesis [6-8] and the IMC-PID approach [4,5,7-14]. Then, in the second step, the robust stability analysis [9,14-16] is utilized for enhancing the robustness of proposed PI control systems. The most important feature of the proposed method is that the tradeoffs between the robust stability and performance can be established by adjusting only one design parameter (i.e., the closed-loop time constant) via the structured singular value synthesis. Moreover, the proposed method can provide a simple multi-loop PI tuning rule in terms of analytical derived, model-based, and able to applied to various multi-delay processes.

The simulation results demonstrate that the proposed method affords the excellent performance in compared with other prominent methods.

II. GENERALIZED MULTI-LOOP CONTROLLER DESIGN

Fig. 1 shows a block diagram of the multi-loop feedback control, where $\tilde{\mathbf{G}}_C(s)$ is the multi-loop PI controller, y(s) and r(s) are the controlled variable and set-point vectors, respectively. Accordingly, the closed-loop transfer function matrix between the set points and outputs can be written as

$$\mathbf{H}(s) = (\mathbf{I} + \mathbf{G}(s)\tilde{\mathbf{G}}_C(s))^{-1}\mathbf{G}(s)\tilde{\mathbf{G}}_C(s) \tag{1}$$

For the design of the multi-loop controller with n diagonal components, let $\tilde{\mathbf{H}}(s)$ be a diagonal matrix consisting of a desired closed-loop transfer function of each loop. Then, $\tilde{\mathbf{G}}_C(s)$ to give the desired diagonal elements can be related to $\tilde{\mathbf{H}}(s)$ as

$$\begin{aligned}\tilde{\mathbf{H}}(s) &= diag[(\mathbf{I} + \mathbf{G}(s)\tilde{\mathbf{G}}_C(s))^{-1}\mathbf{G}(s)\tilde{\mathbf{G}}_C(s)] \\ &= diag[(\mathbf{G}^{-1}(s)\tilde{\mathbf{G}}_C^{-1}(s) + \mathbf{I})^{-1}]\end{aligned} \tag{2}$$

The proposed tuning method is targeted for the processes with modest interactions and diagonal dominance. The inverse of matrix can be reasonably approximated as

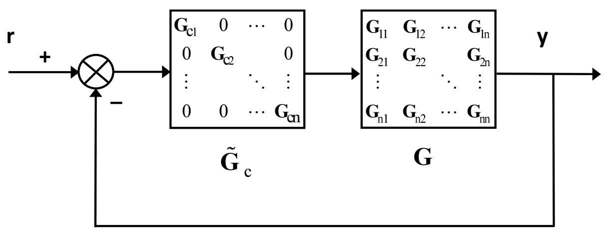

그림 1. 다중루프 제어시스템 블록선도.

Fig. 1. Block diagram of the multi-loop feedback control.

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$$\tilde{\mathbf{H}}^{-1}(s) = \left\{diag\left[\left(\mathbf{G}^{-1}(s)\tilde{\mathbf{G}}_C^{-1}(s)+\mathbf{I}\right)^{-1}\right]\right\}^{-1} \cong diag\left(\mathbf{G}^{-1}(s)\tilde{\mathbf{G}}_C^{-1}(s)+\mathbf{I}\right) \quad (3)$$

According to Truong and Lee [5,8], the multi-loop controller can be obtained by using some linear algebra, as shown in the following procedure:

$$\begin{aligned}\tilde{\mathbf{G}}_C(s) &= diag\{g_{ci}(s)\} \\ &= diag\left(\mathbf{G}^{-1}(s)\right)\left(\tilde{\mathbf{H}}^{-1}(s)-\mathbf{I}\right)^{-1} \\ &= diag\left(\frac{\mathbf{G}^{ii}(s)}{|\mathbf{G}(s)|}\left(\tilde{\mathbf{H}}^{-1}(s)-\mathbf{I}\right)^{-1}\right) \\ &= diag\left(\Lambda_{ii}(s)g_{ii}^{-1}(s)\left(\frac{h_{ii}(s)}{1-h_{ii}(s)}\right)\right)\end{aligned} \quad (4)$$

It is important to note that $\Lambda_{ii}(s) = g_{ii}(s)\frac{\mathbf{G}^{ii}(s)}{|\mathbf{G}(s)|}$ is the diagonal element of the frequency-dependent relative gain array (RGA) for $\mathbf{G}(s)$ given by Bristol [17], of which $|\mathbf{G}(s)|$ is the determinant of $\mathbf{G}(s)$, the scalar $\mathbf{G}^{ij}$ denotes the cofactor corresponding to g_{ij} in $\mathbf{G}(s)$, $adj(\mathbf{G}(s))$ is the adjoint of $\mathbf{G}(s)$, and thus $adj(\mathbf{G}(s)) = \left(\mathbf{G}^{ij}\right)^T = \left(\mathbf{G}^{ji}\right)$. Note that $\mathbf{G}^{ii}$ is the *i*th diagonal element of $adj(\mathbf{G}(s))$. Under the assumption of stable and causal $\Lambda_{ii}(s)$, the desired closed-loop transfer function $h_{ii}(s)$ of the *i*th loop is chosen as $h_{ii}(s) = \frac{e^{-\theta_{ii}s}}{(\lambda_i s+1)^{r_i}}\prod_{k=1}^{q_i}\frac{-s+z_k}{s+z_k^*}$ by considering the IMC theory [9], where θ_{ii}, z_k, and z_k^* denote the time delay, the RHP zeros, and the corresponding complex conjugate of RHP zeros of the *i*th diagonal element of the process transfer function matrix, respectively. q_i is the number of the RHP zeros. The IMC filter time constant, λ_i, which is also equivalent to the closed-loop time constant, is an adjustable parameter controlling the tradeoffs between the performance and robustness. r_i is the relative order of the numerator and denominator in the diagonal elements of process transfer function matrix represented by $g_{ii}(s)$.

III. MULTI-LOOP IMC-PI CONTROLLER DESIGN PROCEDURE

The resulting multi-loop controller given in Eqn. 4 is complicated and unaccepted in practice, and thus it is essential to transform this controller into the more practicable PI controller, which is one of the most acceptance controllers in the process industry. For the sake of simplicity, the Maclaurin series expansion based approach [4] is used as following procedure:

Since the *i*th controller of multi-loop feedback controller has the integral term for offset free, $g_{ci}(s)$ can be rewritten as

$$g_{ci}(s) = \frac{p_i(s)}{s} \quad (5)$$

Thus,

$$p_i(s) = diag\left\{\Lambda_{ii}(s)g_{ii}^{-1}(s)\left(\frac{h_{ii}(s)}{1-h_{ii}(s)}\right)\right\}s \quad (6)$$

The rational approximation form of Eqn. 5 can be expanded by using the Maclaurin series

$$g_{ci}(s) = \frac{1}{s}\left[p_i(0) + sp_i'(0) + \ldots\right] \quad (7)$$

The first two terms of the above equation can be constituted as the standard PI controller given by

$$g_{ci}(s) = \frac{1}{s}\left(K_{Ii} + sK_{Ci}\right) \quad (8)$$

where K_{Ii} and K_{Ci} are the integral and proportional terms of the standard PI controller, respectively.

Comparing Eqn. 7 and Eqn. 8, the proposed PI controller parameters can be found by

$$K_{Ci} = p_i'(0) \quad (9)$$

$$K_{Ii} = p_i(0) \quad (10)$$

As it can be seen from Eqns. 9 and 10, the controller parameters K_{Ci} and K_{Ii} can be easily found if the closed-loop time constant $\lambda_i(i=1,2,\ldots,n)$ is determined. Note that λ_i is also the adjustable parameter. Therefore, the proposed multi-loop PI controller can be obtained for enhancing the robust performance of overall control system by adjusting λ_i.

IV. ROBUST STABILITY ANALYSIS

In control system design, the nominal model is only used as an approximate representation of the actual system. The discrepancies between the actual system and its mathematical representation (nominal model) are referred to as model/plant mismatch (model uncertainty) may lead to a violation of some performance specification. Therefore, a control system is stable if the control system is insensitive to the variation in the dynamics of the plant (including various possible uncertainties) [9,14-16]. Therefore, in this paper, the robust stability analysis is carried out by inserting the multiplicative output uncertainty in each of the process parameters simultaneously as shown in Fig. 2, which can be written as follows:

$$\Pi_O : \quad \mathbf{G}_p = \mathbf{G}[\mathbf{I}+\mathbf{E}_O]; \quad \mathbf{E}_O = \mathbf{W}_O\boldsymbol{\Delta} \quad (11)$$

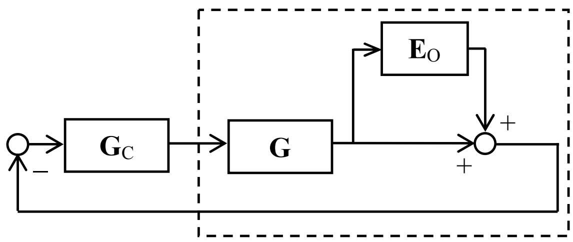

그림 2. 곱 형태의 출력 불확실성.

Fig. 2. Multiplicative output uncertainty.

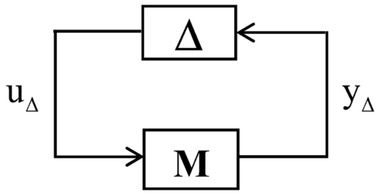

그림 3. 강건성 분석을 위한 일반적 M-Δ 제어구조.

Fig. 3. General M-Δ control structure for robustness analysis.

Note that $\mathbf{\Pi}_O$ denotes a set of output perturbed process models. $\mathbf{G}_p$ is the n x n transfer function matrix of process models as the perturbation of its nominal process model $\mathbf{G}$ due to the uncertainty as multiplicative output, $\mathbf{E}_O$. The magnitude of the perturbation $\mathbf{E}_O$ can be measured in terms of a bound on $\bar{\sigma}(\mathbf{E}_O)$.

$$\bar{\sigma}(\mathbf{E}_O) \le \mathbf{W}_O(\omega), \ \forall\omega \tag{12}$$

where the bound (weight) $\mathbf{W}_O(\omega)$ can also be interpreted as a scalar weight on a normalized perturbation $\Delta(s)$ with $\bar{\sigma}[\Delta(j\omega)] \le 1, \ \forall\omega.$

The structured singular value synthesis, which can be called as the μ-synthesis, suggested by Doyle [15] is utilized here as the robustness measurement of proposed PI control systems. Any perturbation blocks can be rearranged into the the general **M-Δ** control structure, which is shown in Fig. 3, where Δ is the perturbation block with $\bar{\sigma}(\Delta) \le 1, \ \forall\omega$ and **M** involves all other blocks such as the plant, controller, and weighting factors.

For the multivariable process with multiplication output uncertainty, the transfer function matrix from the outputs to the inputs of Δ can be determined by comparing Fig. 2 and Fig. 3.

$$\mathbf{M} = -\mathbf{G}\tilde{\mathbf{G}}_C\left(\mathbf{I}+\mathbf{G}\tilde{\mathbf{G}}_C\right)^{-1}\mathbf{W}_O \tag{13}$$

According to the structured singular value synthesis, the multi-loop control system will remain stable under the multiplication output uncertainty if the following inequality constraint is satisfied:

$$\mu(\mathbf{M}(j\omega)) = \mu\left(\mathbf{G}\tilde{\mathbf{G}}_C\left(\mathbf{I}+\mathbf{G}\tilde{\mathbf{G}}_C\right)^{-1}\mathbf{W}_O\right) < 1, \ \forall\omega \tag{14}$$

Note that **M** and Δ are required stable.

Remarks:

1. $\mu(\mathbf{M}(j\omega))$. In this situation, there does not exist any perturbation in the multi-loop control system.
2. $\mu(\mathbf{M}(j\omega)) = 1$. It is indicated that there exists a perturbation with $\bar{\sigma}(\Delta) = 1$, which is just large enough to make $\mathbf{I} - \mathbf{M\Delta}$ singular.
3. A smaller value of $\mu(\mathbf{M}(j\omega))$ is good. Inversely, a larger value of $\mu(\mathbf{M}(j\omega))$ is bad because it means that a smaller perturbation makes $\mathbf{I} - \mathbf{M\Delta}$ singular.

V. SIMULATION STUDY

In this section, two examples are considered to demonstrate the flexibility and effectiveness of the proposed method in comparison with those of other well-known methods. For a fair comparison of controller performance, some performance criteria such as the integral absolute error (IAE) and the integral of the time-weighted absolute error (ITAE) can be used for evaluating the closed-loop performance. Both of them can provide a good performance metric. In this study, the IAE criterion is arbitrarily selected for the evaluation of the controller performance.

Example 1: Vinante and Luyben (VL) column.

The 24-tray tower separating a mixture of methanol and water examined by Luyben [1] has the transfer function matrix given as

$$\mathbf{G}(s)=\begin{bmatrix} \dfrac{-2.2\,e^{-s}}{7s+1} & \dfrac{1.3\,e^{-0.3\,s}}{7s+1} \\ \dfrac{-2.8e^{-1.8\,s}}{9.5s+1} & \dfrac{4.3e^{-0.35\,s}}{9.2s+1} \end{bmatrix} \tag{15}$$

To illustrate the robustness of the proposed method, assume there actually exists the multiplicative output uncertainty $\mathbf{W}_O$ = $diag\{(s+0.2)/(2s+1),\ (s+0.2)/(2s+1)\}$, which can be physically regarded as that the relative uncertainty decrease with up to 50% in the high frequency range and with almost 20% in the low frequency range at about 1 rad/min. The uncertainty is represented as the multiplicative output uncertainty as shown in Fig. 2.

According to the μ-synthesis for the multiplicative output uncertainty, a set of the adjustable parameters λ_i are suggested to achieve a desirable specification of robust stability and performance by increasing them monotonously. Fig. 4 shows the magnitude plot of the structured singular value used for measuring the robust stability in the proposed method, where the optimum values of λ_i are obtained as 1.55 and 0.35 for loops 1 and 2, respectively. It is clear that the maximum value of μ is less than unity. Therefore, the proposed control system is guaranteed the robust stability.

Our extensive studies have been made for various multi-delay processes, which have indicated that when λ_i are setting as the small values, the proposed nominal control system can achieve great improvement with corresponding to small IAE values and fast output responses. However, the robustness of control system

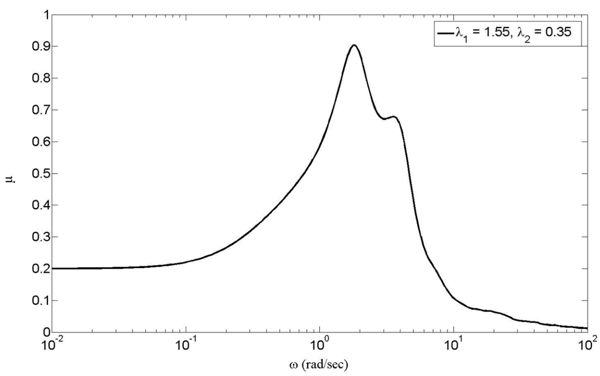

그림 4. VL 증류탑의 구조특이값.

Fig. 4. Magnitude plot of the structured singular value for the VL column.

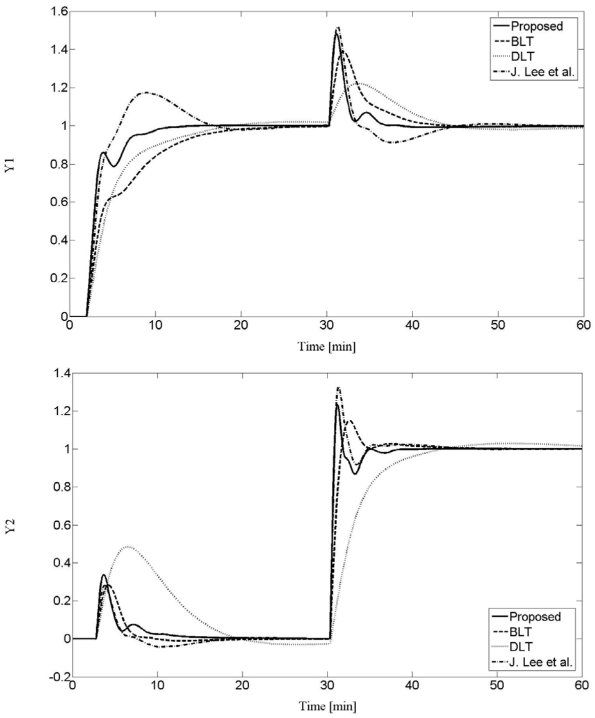

그림 5. VL 증류탑의 폐루프 응답.

Fig. 5. Closed-loop time responses for the VL column.

표 1. VL 증류탑 예에 대한 여러가지 방법에서의 PI 제어기 매개변수 값과 IAE 값.

Table 1. PI controller parameters and IAE values obtained by various methods for the VL column.

	Proposed	BLT	DLT	J. Lee et al.
K_C	-1.89	-1.07	-0.76	-1.31
	4.66	1.97	0.56	3.97
τ_I	6.54	7.10	4.10	2.26
	8.63	2.58	4.04	2.42
IAE_1	2.59	4.90	4.60	3.48
	0.89	0.79	4.32	0.81
IAE_2	0.95	1.59	1.79	1.48
	1.02	1.33	3.59	1.33
IAE_t	5.45	8.61	14.30	7.10

IAE_i: IAE for the step change in loop i; IAE_t: sum of each IAE_i.

tends to reduce its robust capacities in practice because a small perturbation can make $\mathbf{I}-\mathbf{M\Delta}$ singular. On the other hand, when λ_i are setting as large values, the μ-values will be tended to small values systematically. Therefore, the nominal control system will be tended to surpass their robust capacities in practice. In this paper, we consider the tradeoffs between the performance and robustness in order that a set of λ_i are suggested to achieve a desirable specification of the robust stability and performance.

The resulting multi-loop PI controllers by various design methods are listed in Table 1. The closed-loop time responses tuned by the proposed, BLT [1], DLT [18], and J. Lee et al. [19] methods are compared in Fig. 5, which is performed by setting a sequential unit step change in the set-point at t=0 and t = 30. It is apparent that the proposed PI control system provides more well-balanced and faster nominal responses in compared with the other methods. Besides, the superiority of the proposed method is also confirmed by IAE values in Table 1.

Example 2: Alatiqi case 2 (A2) column.

The transfer function matrix model for the A2 column was introduced by Luyben [1] as follows:

$$\mathbf{G}(s)=\begin{bmatrix} \frac{4.09e^{-1.3s}}{(33s+1)(8.3s+1)} & \frac{-6.3e^{-0.2s}}{(31.6s+1)(20s+1)} & \frac{-0.25e^{-0.4s}}{(21s+1)} & \frac{-0.49e^{-5s}}{(22s+1)^2} \\ \frac{-4.17e^{-4s}}{(45s+1)} & \frac{6.93e^{-1.01s}}{(44.6s+1)} & \frac{-0.05e^{-5s}}{(34.5s+1)^2} & \frac{1.53e^{-2.8s}}{(48s+1)} \\ \frac{-1.73e^{-17s}}{(13s+1)^2} & \frac{5.11e^{-11s}}{(13.3s+1)^2} & \frac{4.61e^{1.02s}}{(18.5s+1)} & \frac{-5.48e^{-0.5s}}{(15s+1)} \\ \frac{-11.18e^{-2.6s}}{(43s+1)(6.5s+1)} & \frac{14.04e^{-0.02s}}{(45s+1)(10s+1)} & \frac{-0.1e^{-0.05s}}{(31.6s+1)(5s+1)} & \frac{4.49e^{-0.6s}}{(48s+1)(6.3s+1)} \end{bmatrix} \quad (16)$$

To demonstrate the robust stability of the proposed control system against the process multiplicative output uncertainties, assume that there exist the multiplicative output uncertainty $\mathbf{W}_O(s)$ = $diag$\{(s+0.2)/(2s+1), (s+0.2)/2s+1), (s+0.2)/(2s+1), (s+0.2)/(2s+1)\}. This implies all of the process output actuators decrease with up to 50% uncertainty at high frequency range and almost 20% uncertainty in the low frequency range at about 1 rad/min. By using the μ-synthesis, the λ_i values can be found as 7.30, 1.20, 4.60, and 9.40 for 1, 2, 3, and 4 loops, respectively, and thus the proposed control system is guaranteed the robust stability as shown in Fig. 6.

Fig. 7 shows the closed-loop time responses obtained by the proposed and BLT [1] methods, where the unit step changes in set-point were sequentially made in the individual loops for testing the performance of the control systems. It is evident from

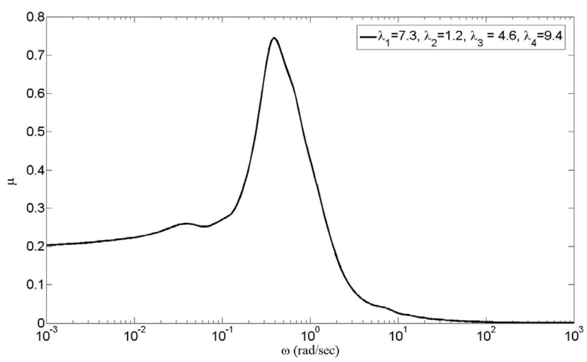

그림 6. A2 증류탑의 구조특이값.

Fig. 6. Magnitude plot of the structured singular value for the A2 column.

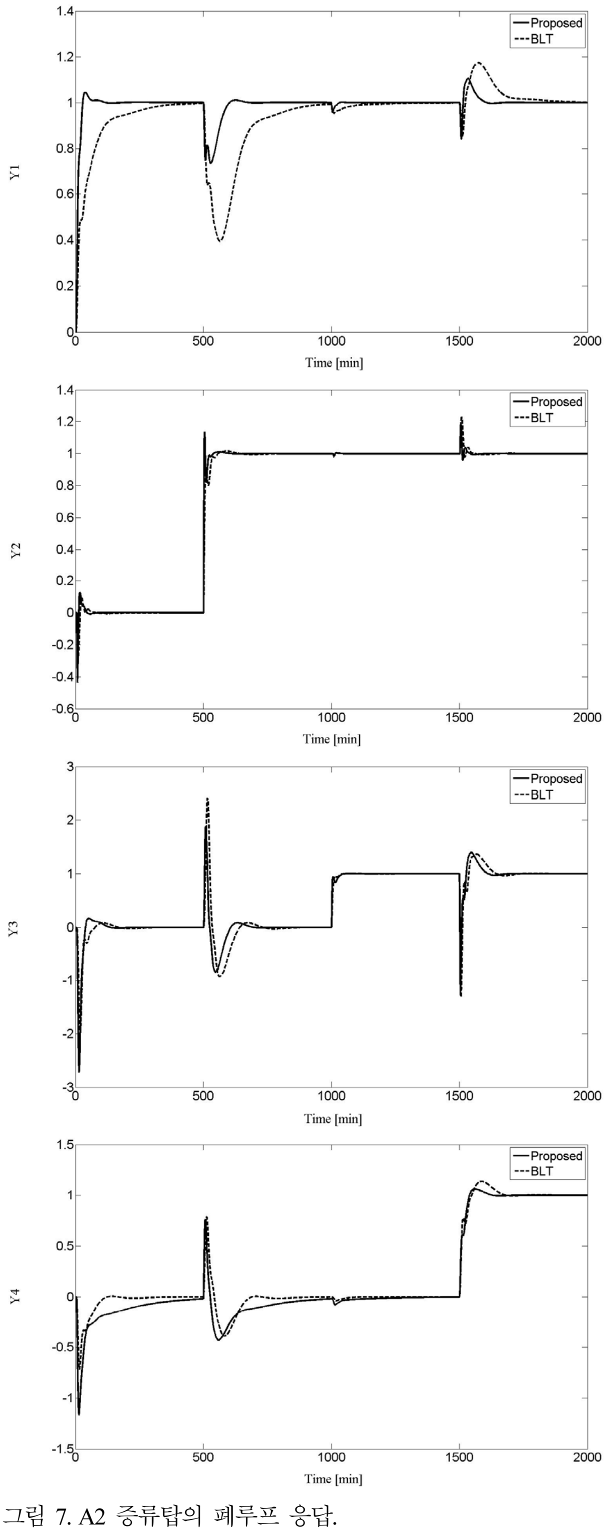

그림 7. A2 증류탑의 폐루프 응답.

Fig. 7. Closed-loop time responses for the A1 column.

this figure that the improved system performance is obtained by the proposed method. Moreover, the proposed multi-loop control system holds the robust stability well in terms of the fast and well-balanced responses over the BLT methods.

The resulting controller parameters, together with the performance indices, are given in Table 2. It can be seen that the closed-loop response by the proposed PI controller provided the smallest total IAE value.

표 2. A2 증류탑 예에 대한 여러가지 방법에서의 PI 제어기 매개변수 값과 IAE 값.

Table 2. PI parameters and IAE values obtained by various methods for the A2 column.

	Proposed	BLT
K_C	2.40, 3.38, 1.54, 3.23	0.92, 1.16, 0.73, 2.17
τ_I	27.2, 14.37, 25.8, 169.7	61.7, 13.2, 13.2, 40
IAE_1	12.16, 4.08, 48.7, 78.25	50.96, 4.25, 43.3, 27.8
IAE_2	15.11, 4.55, 63.75, 67.6	80.96, 9.4, 99.5, 47.16
IAE_3	0.64, 0.19, 6.01, 4.98	3.25, 0.19, 6.68, 1.76
IAE_4	5.83, 1.7, 40.25, 17.12	21.65, 3.28, 53, 24.6
IAE_t	370.92	477.74

VI. CONCLUSIONS

A simple analytical design method for robust multi-loop PI controllers was proposed based on the direct synthesis and IMC-PID approach for the multi-delay processes. The proposed PI control system can be afforded the excellent performance, since the robustness in the multi-loop system can be satisfactorily guaranteed by using the μ-synthesis. The simulations were conducted by tuning various multi-loop PI controllers for the multi-delay processes, and the proposed PI controllers were confirmed to be superior to several well-known existing methods.

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